SHOCK WAVE GENERATORS

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Abstract

Flux compression generators (FCGs) are high-energy power supplies that are capable of delivering joules to megajoules to loads. There are different types of generators, where each type has its advantages and disadvantages. One possible significant disadvantage of all FCGs is high G-force survivability. To address this issue, a new FCG design is being developed. This new generator, called a Shock Wave Generator (SWG), replaces the standard air filled armature with a powder or a solid, which under shock pressures transitions from a dielectric to a metallic state. This moving metallic shock front is used to convert the chemical energy of high explosives into electrical energy. In this paper, we will report on recent experimental studies of these generators.

I. INTRODUCTION

Flux Compression Generators (FCGs) have been under development since the early 1950s. There are generally two applications for FCGs. The first is as a source for ultra high magnetic fields, and the second is as high-energy power supplies for driving a variety of loads such as lasers, microwave sources, x-ray sources, z- and Θ-pinches, telemetry packages, neutron generators, and railguns. In this paper, we will focus on FCGs in the role of single-shot power supplies.

These generators consist of a seed (initial energy) source, explosive charge, armature, stator, and output circuit. They work in the following way. The seed source delivers an electric current to the armature-stator circuit, creating a magnetic field. When the field reaches its peak value, the explosive charge is initiated, causing the armature to flare out and trap the magnetic flux inside the generator. As the detonation process continues, the moving flared armature compresses the magnetic field, amplifying the initial current from the seed source. These generators are typically gas filled.

In recent years, a new type of FCG has been proposed in which the moving metal armature is replaced by a moving conductive shock front. It has long been known that certain dielectrics become electrically conducting under high pressures associated with shock waves. The new approach is to replace the void or gas in the standard FCG with a working material and to shock it with explosives producing an expanding conducting shock front that is used to compress the magnetic field. This new type of FCG is called a Shock Wave Generator (SWG). Some of the potential advantages of these generators are ruggedness, possibly high voltage hold-off, and reduced losses due to instabilities such as Rayleigh-Taylor instabilities.

In this paper, we will present some of the results of recent experiments with Shock Wave Generators. Some of our recent results show that

- Certain powder mixtures are better than others,

- Particle size and packing are critical factors, and

- Current gains as good as or better than air have been achieved in some filled cylindrical generators tests.
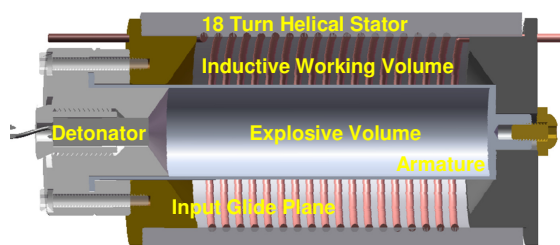

Figure 1. Parts of a flux compression generator.

FCGs in general and helical units in particular function with a void in the inductive volume, usually filled with air, a specific gas such as sulfur hexafluoride, or vacuum, Figure 1. Thus, a conventional helical FCG has a coaxial aluminum tube, the armature, which is filled with explosive within the outer housing or stator. Such a configuration is intrinsically very difficult or impossible to harden to

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1. REPORT DATE **JUN 2011**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**	
4. TITLE AND SUBTITLE **Shock Wave Generators**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Space and Missile Defense Command/Army Strategic Forces Command Redstone Arsenal Huntsville, AL, USA**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
Flux compression generators (FCGs) are high-energy power supplies that are capable of delivering joules to megajoules to loads. There are different types of generators, where each type has its advantages and disadvantages. One possible significant disadvantage of all FCGs is high G-force survivability. To address this issue, a new FCG design is being developed. This new generator, called a Shock Wave Generator (SWG), replaces the standard air filled armature with a powder or a solid, which under shock pressures transitions from a dielectric to a metallic state. This moving metallic shock front is used to convert the chemical energy of high explosives into electrical energy. In this paper, we will report on recent experimental studies of these generators.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **6**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

high G loads, >10,000 Gs. Further, FCGs have additional possible disadvantages, including instabilities (e.g., Rayleigh-Taylor) and several loss mechanisms including clocking flux losses, magnetic diffusion, and so on that can lead to significant losses when even moderate G loads result in small displacements of the armature relative to the stator.

The magnetic flux compression is accomplished through a process that transitions a dielectric into a metallic state under shock conditions. The propagating metallic shock in the "working material" would take the place of the armature motion in conventional FCGs. The presence of this material may also serve to G harden the generator against sudden or extreme accelerations simply by preventing displacement of the explosive loaded armature/pusher.

As indicated, the inductive volume of a shock wave generator is filled with a material that becomes conductive under the influence of a shock. While this material is usually in the form of a powder which by itself has no strength, it does serve to fill the void and prevent motion. It has been proposed that some instabilities and loss mechanisms can, at least partially, be eliminated by compressing the FCG's magnetic flux in solids such as ionic salts, semiconductors, or oxide coated metal powders. One way to understand how a reduction to clocking losses might be achieved is to understand that under G loading the armature would not be able to flex or to be displaced from a concentric position within the stator. Thus, the armature and subsequent shock wave would retain the required geometry within the generator volume for "normal" operation.

II. HISTORICAL PERSPECTIVES

In the early 1960s, it was found that certain dielectrics, such as silicon, and oxidized metal powders become electrically conducting under static and shock compression. It was found that under static compression, the electrical conductivity of silicon increases monotonically with increasing pressure and reaches the conductivity of classic metals. In addition, it was also found that shock compression of silicon causes metallization to occur when the Hugoniot Elastic Limit is exceeded. The difference between the static compression induced conductivity and the shock induced conductivity in silicon is that the shock conductivity was found to be six orders of magnitude better at a pressure of 15 GPa. Other substances that exhibit this property are germanium, selenium, gray tin, silicon oxide, cesium iodide, germanium iodide, and lithium niobate ($LiNbO_3$).

The first SWGs were built and tested by K. Nagayama and his team at Kumamoto University [1,2]. They used both single crystal cylinders of silicon and silicon powder in their experiments. The generators were cylindrical implosion designs. Both the single crystal and the powder silicon generated large signals with field gains of almost 18.

At about the same time, E.I. Bichenkov and his team [3]) began a similar series to studies. He reported on using both silicon filled planar and coaxial FCGs. He noted that there was a significant dependence of the generator parameters on the ratio of the mass velocity to the velocity of the shock wave in silicon. This work continues today under S.D. Gilev [4]..

Others who contributed to the development of these generators were Barmin and Prishchepenko [5], [6] Bjarnholt et al. [7], Novac et al. [8], and Hemmert [9]

III. TECHNICAL CHALLENGE

With the exception of a few cylindrical generator tests, virtually all of the successful SWGs have involved cylindrical implosion systems. The difficulty with this geometry is that it is generally not well suited for use in the role of a power supply, and the quantity of explosive required for the same length system is significantly larger, often by a factor of 4 to 5, than required for a conventional divergent FCG. Also, divergent FCGs, such as conventional helical generators, have been used as power supplies for several decades. Thus, the challenge in this effort has been to find materials with sufficiently low transition pressures to enable the conventional-geometry, divergent FCG geometries to be used as SWGs.

IV. STUDY OBJECTIVES

The primary objective of this development effort is to find material(s) that may be used as the working material within a SWG to achieve gains similar or better than the equivalent "air" filled generators. The ultimate objectives of these studies are to develop SWGs as potential power supplies for use in high G-force environments and to determine if these generators can be used in applications that are not possible with conventional FCGs.

Unlike previous SWGs, which were implosion designs, the generators used in these studies were explosive generators. That is, the previous generators produced a converging ionized shock front that was used to compress the magnetic field, while the generators used in these current studies were based on conventional cylindrical and helical design, where the

ionized shock front travels radially outward from the center of the generator. In the former case, the objective was to generate high fields, while in the latter case the objective was to produce electrical current.

The form factor for these FCGs is generically a ~2.54-cm outer diameter armature. All generators involved in this research use a common design, aluminum armature. The outer diameter of the common armature is 2.54 cm, and the armature wall thickness is ~0.75 mm. The stator designs all have a ~50-cm inner diameter. The length of the explosive volume is 9.27 cm. The explosive used is Composition C4.

Four generator designs were investigated. The first is a cylindrical design and the other three are helical designs. All generators involved in this research used a common design, aluminum armature. Many common parts are shared among these four generator designs to lower the cost per shot of the testing. The three different helical generator designs are standardized so that only the stator is changed. This feature allows for direct comparisons between different tests.

V. SWG MATERIAL CONCEPTS

Generally, we have examined three broad classes of materials for this effort. These classes may be described as (1) those materials, usually pure elements, whose conduction band is accessible with the application of pressure, (2) materials that are metals with oxide coatings, and (3) materials identified as Mott insulators. The first class of materials is represented by silicon, germanium, selenium, and some of the ionic compounds such as salt in the form of KCl. For example, pure silicon in both powder and single crystal form transitions to a metallic-like conductor with the application of ≥ 15 GPa (150 kbar) of pressure either statically or transiently from the passage of a shock wave. The second class of materials is most commonly represented by powdered aluminum. As commonly acknowledged, aluminum will form an oxide coating when exposed to air. If the powder is fine, though not too fine, (≥ 5 µm), one will have a metal powder with a resistive oxide coating. When this material is subjected to a strong shock, the oxide coating is compromised such that the metal cores of the powder will contact, transitioning the bulk from insulator to conductor. The third class of materials is known as Mott insulators. These are materials that, from conventional band gap theory, should be conductors but are in fact insulators. Unlike conventional band gap theory, the bandgap in a Mott insulator exists between bands of like character such as the 3d levels. Examples of Mott insulators include the transition metal oxides as well as the high temperature

superconductor compounds. For several of these materials, the application of pressure will close the energy gap between conduction states, causing a transition to a conducting state.

VI. EXPERIMENTAL RESULTS

During the course of this study, many materials were experimentally tested. In total, 22 materials have been tested. Generally, there were eight (8) materials in the first class of materials, one (1) material in the second class, nine (9) materials in the third class, and six (6) types of thermite materials.

A significant amount of research examined the possibility of using thermite to achieve fast ignition and high conductivities. We recognized that a major obstacle with this approach was that the REDOX reactions for thermite required high initiation energies and that the ignition propagation can be relatively slow compared to generator time scales. To address these questions nanopowder thermite and several mixtures of powder explosive and Composition C4 were tested, along with several input geometries to reflect and enhance shocks at the start of the generator. Unfortunately, we finally had to conclude that some of the Mott insulators that are also components of thermite were a better explanation for encouraging results than the thermite reactions.

To test a new candidate material, the first step is often to measure the material's effective resistance in a simulated geometry to that of a generator. This measurement enabled a determination of the necessity of either partly or completely insulating the interiors of the generator tests. The next step is to build, load with material, and fire a cylindrical generator test. Often, the results from the test of these simple generators were sufficient to preclude a more expensive experiment involving a helical generator. Nevertheless, an encouraging result in a cylindrical generator test indicates that a helical generator experiment should be performed.

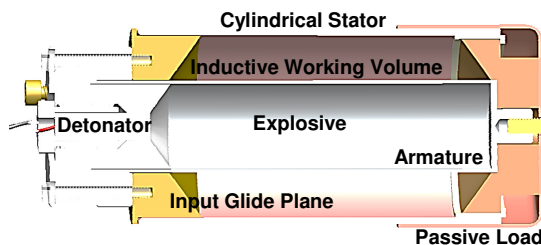### A. Cylindrical Generators

Figure 2. Cylindrical Generator

Cylindrical generators (Fig. 2) do not achieve high gains because the working volume inductance is relatively small. However, their simple design enables easy detection of flux losses. The inductance of the generator volume for the standard cylindrical system used in this effort is ~8.6 nH. The load inductance is tightly fixed by the generator construction and has an inductance of ~1.2 nH. The estimated realistic current gain for this generator is ~6.3:1, assuming reasonable losses. The best current gain achieved for this generator design is ~5.4:1.

All discussion of the results of the tests will use the dI/dt signals since these data are far more sensitive to generator performance. As far as possible, all of the traces have been set to time zero at the crowbar for the generator. The time duration is typically ~16 µs to enable direct comparisons between traces.
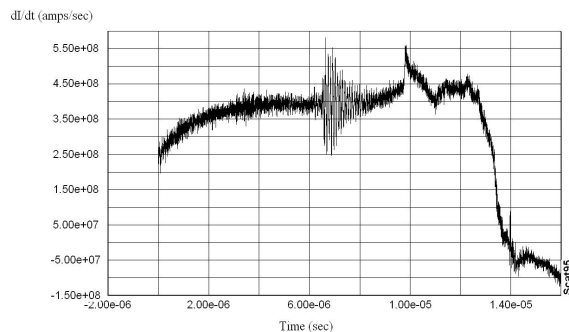

Figure 3. dI/dt trace from powdered silicon cylindrical generator test.
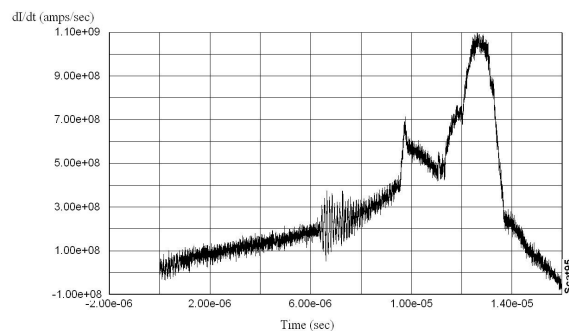

Figure 4. dI/dt trace from aluminum/aluminum oxide powder cylindrical generator test.

The first materials tested belong to the first class of materials properties, namely pure elements or simple compounds. An example of the test data obtained from this group of tests is provided by the dI/dt trace from the silicon powder experiment, Figure 3. The spike in the data just before 10 µs is common for most of the experiments and represents the arrival of the shock at the stator diameter. The value of dI/dt barely rose above 4.5×10^8 amps/sec and the current gain was

~2.75:1. Though the Idot did not get very large, it did stay at a significant level for a relatively long time.

The second class of materials of interest was the metal/metal oxide powders. As indicated, aluminum powder is perhaps the best representative of this group. The data for one of the aluminum experiments is shown in Figure 4. Unlike the silicon test, the dI/dt for this test exceeded $\sim 1 \times 10^9$ amps/sec, though the current gain was only ~2.45:1, somewhat less than for the silicon test. One will notice that after the jump in dI/dt before 10 µs, the value decreased until ~11 µs. Given several experiments using aluminum in the cylindrical geometry, the reproducibility was very disappointing.
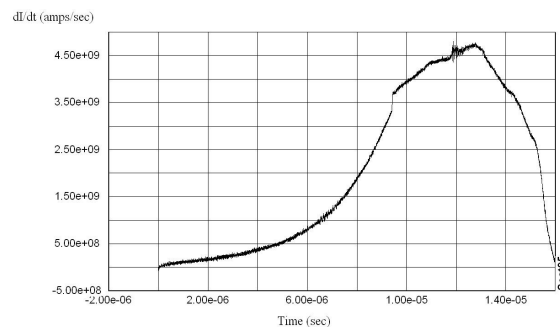

Figure 5. dI/dt trace from LaSrMnO$_3$ cylindrical generator test.

Of the powders tested in this generator, the most encouraging results were obtained with LaSrMnO$_3$, a Mott insulator and a material used for thermal cathodes. Unlike the earlier two examples, the dI/dt trace smoothly ramps up until the jump before 10 us, Figure 5. From this time, the current derivative continues to increase and reaches a maximum value $>4.5 \times 10^9$ amps/sec. The associated current gain for this experiment is ~10.9:1, larger than the air gain of ~5.4:1.
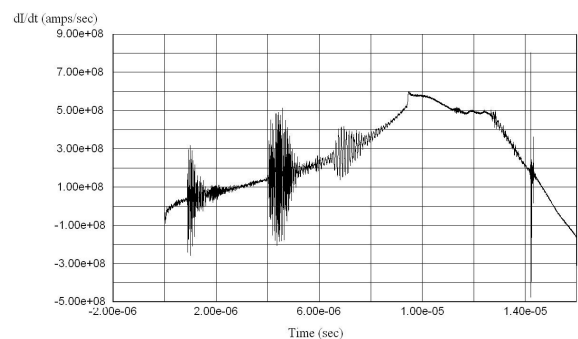

Figure 6. dI/dt trace from SrTiO$_3$ powder cylindrical generator test.

While the Mott insulator materials remain a serious interest for the SWGs, some of these materials have not provided much encouragement. Figure 6 shows the

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dI/dt trace for the cylindrical generator test of SrTiO$_3$, another Mott insulator. In some respects, this trace is somewhat similar to the silicon powder results. Unlike silicon, SrTiO$_3$ ramps relatively smoothly in magnitude until the jump, noted earlier. After this time, the dI/dt declines in value to holding steady until generator burnout, as in the experiment with silicon.
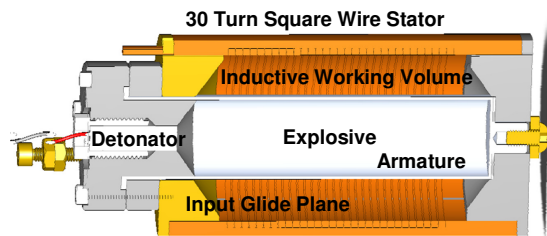
B. Helical Generators

Figure 7. 30-turn, square-wire helical generator.

Helical generators generally tend to have higher gain than cylindrical generators due to their larger initial inductance. Within this effort three different helical generators, each with differing electrical and shock characteristics have been used. All three generators have been tested with "air" filling to determine the experimental gains. One of these generator designs was explicitly intended to provide a helical inductance (~20 µH) while providing an approximation for a cylindrical generator in terms of shock behavior within the unit, Figure 7. Several different powders have been studied in each generator. However, none of the class of materials in the pure elements were used in these tests because there was little indication from the cylindrical tests that they would demonstrate desired function.
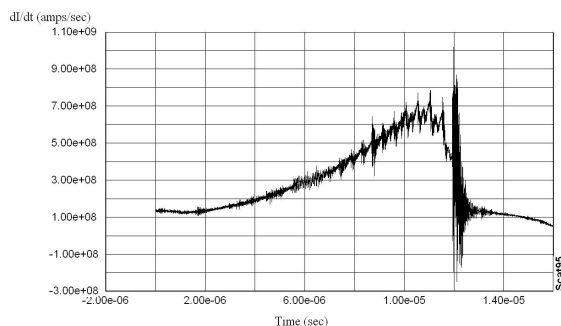

Figure 8. dI/dt trace from 30 µm aluminum powder helical generator test.

Several aluminum/aluminum oxide powder tests have been performed with the helical generators. Surprisingly, the most encouraging of these experiments used 30 µm powder, rather than the powders in the range of 5-10 µm. The dI/dt trace from this test is shown in Figure 8. This experiment used the

18-turn, helical stator generator (~6.7 µH) that has been a workhorse for this portion of the effort. The trace shows a generally smooth increase until ~11.5 µs when it begins decreasing. The interesting characteristic is the appearance of clocking during the generator run. This suggests that there is an interaction between the powder and the helical stator. Unfortunately, the current gain for this test was ~6.8:1, compared with the air gain of about 10.5:1. As noted earlier, the aluminum performance remained very uneven and unpredictable.
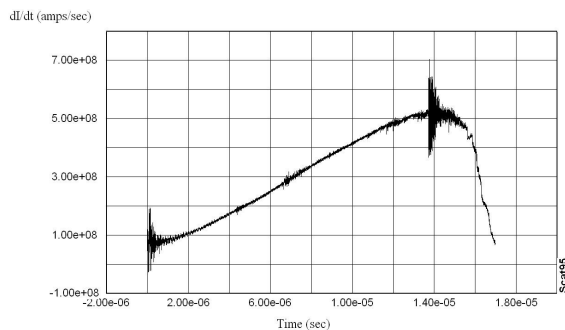

Figure 9. dI/dt trace from LaSrMnO3 helical generator test with square wire stator.

While LaSrMnO3 demonstrated very encouraging performance in the cylindrical generator, it did not provide encouraging results when used in all three different versions of the helical generator. Figure 9 show the dI/dt trace from the square wire generator design shown in Figure 7. One will note that the maximum dI/dt value of >5x10^8 amps/sec is less than the ~6x10^8 amps/sec observed in the aluminum test. The current gain for this experiment was ~2.1:1, much less than for the aluminum.

C. Promising Working Materials

There have been ~22 distinct powders tested in this program with several admixtures in addition to these. The class of materials represented by the pure elements has been very disappointing. It is worth repeating from the background discussion that several of these materials have shown significant performance when used in implosion geometries. Nevertheless, the silicon data provided here is representative of these materials in our divergent-geometry generators.

From the second class of materials, aluminum powder was the one studied. Tantalum is another of these materials, but it is very toxic. Generally, we did observe the aluminum powder to perform comparatively better than the pure elements. On one or two tests, aluminum even approached the performance of an air-filled generator. This would have made aluminum a candidate material. Unfortunately, the

performance of aluminum was very unpredictable. On one test, the current gain would compete with air, and on another the gain would be very small. Thus, we must conclude that with proper care, one may be able to demonstrate comparable current gains to air in cylindrical generators with aluminum powder. Unfortunately, a similar result was not observed for the helical tests.

The third class of materials, Mott insulators, offer perhaps the greatest potential for finding a material that will be able to replace air within an explosive generator. Certainly, $LaSrMnO_3$ used within a cylindrical generator demonstrated a very substantial current gain improvement over an air-filled generator. Given a working material that achieves a metallic transition, one might expect such an outcome since air within a generator is repeatedly shocked to increasing temperatures and the volume within the generator is reduced. Unfortunately, this material did not perform well in the context of a helical generator. We had speculated that a helical generator with shock characteristics similar to a cylindrical generator might do better, but this was not supported by experimental results. The fact that a Mott insulator performed well in a cylindrical generator, though not in a helical system is important. This data point moved us from implosion system requirements to a very symmetric divergent design. The class of materials known as Mott insulators begin with the transition metal oxides and extend into materials with valence-shared electrons, much as the high temperature superconductors – many are Mott Insulators. Thus, we conclude that some Mott insulator will likely identified as a useful working material for helical generators.

VII. CONCULSIONS

The primary goal of this research has been to identify and experimentally demonstrate a working material to replace air and other gases within an explosive-driven flux compression generator in a divergent geometry. This goal recognizes the necessity for using this geometry for power-producing FCGs. In pursuit of this goal, we have studied a wide array of materials, some identified in earlier work and many unique to this project. As in other efforts, we found that aluminum powder can work at levels approaching air fills, but the required care and quality control are very serious issues that will have to be addressed. For the divergent cylindrical generators, we have identified at least one material that works much better than air, namely $LaSrMnO_3$, a Mott insulator. There are many reasons to suspect that other Mott insulators will ultimately be useful in a helical generator as well.

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